

BMO TR-81-72

SAI DOCUMENT NO. SAI-067-81R-014

2
LEVEL *111*
2108849

**PERFORMANCE TECHNOLOGY PROGRAM
(PTP-S II)**

VOLUME XII

COUPLING OF THE CM3DT INVISCID NOSETIP FLOW FIELD CODE
TO THE QUICK GEOMETRY AND STEIN AFTERBODY CODES

SCIENCE APPLICATIONS, INC.
APPLIED MECHANICS OPERATION
WAYNE, PENNSYLVANIA 19087

New

JUNE, 1980

FINAL REPORT FOR PERIOD MARCH 1980 - JUNE 1980

CONTRACT NO. F04701-77-C-0126

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AIR FORCE BALLISTIC MISSILE OFFICE
NORTON AIR FORCE BASE, CALIFORNIA 92409

DTIC
ELECTE
S **D**
DEC 28 1981
D

New 412706

81 12 23 125

AD A108850

This final report was submitted by Science Applications, Inc., 1200 Prospect Street, La Jolla, California 92038, under Contract Number F04701-77-C-0126 with the Ballistic Missile Office, AFSC, Norton AFB, California. Major Kevin E. Yelmgren, BMO/SYDT, was the Project Officer in charge. This technical report has been reviewed and is approved for publication.

Kevin E. Yelmgren

KEVIN E. VELMGREN, Major, USAF
Chief, Vehicle Technology Branch
Reentry Technology Division
Advanced Ballistic Reentry Systems

FOR THE COMMANDER

Nicholas C. Belmonte

NICHOLAS C. BELMONTE, Lt Col, USAF
Director, Reentry Technology Division
Advanced Ballistic Reentry Systems

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER BMO TR-81-72	2. GOVT ACCESSION NO. AD-A108	3. RECIPIENT'S CATALOG NUMBER 850
4. TITLE (and Subtitle) "Performance Technology Program (PTP-SII), Vol. XII, Coupling of the CM3DT Inviscid Flow Field Code to the QUICK Geometry and STEIN Afterbody Codes"		5. TYPE OF REPORT & PERIOD COVERED Final Report, 3/80 to 6/80
7. AUTHOR(s) Darryl W. Hall Catherine M. Dougherty		6. PERFORMING ORG. REPORT NUMBER SAI-067-81R-014
9. PERFORMING ORGANIZATION NAME AND ADDRESS Science Applications, Inc. 994 Old Eagle School Rd., Ste. 1018 Wayne, Pennsylvania 19087		8. CONTRACT OR GRANT NUMBER(s) F04701-77-C-0126
11. CONTROLLING OFFICE NAME AND ADDRESS Ballistic Missile Office Norton AFB, California 92409		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Tasks 3.2.1.7, 3.2.1.8
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE June 1980
		13. NUMBER OF PAGES 27
		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Flow Field Blunt Body Code Nosetips		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The CM3DT inviscid blunt body code is modified to include the QUICK geometry description routine. A procedure is developed to couple the CM3DT code to the STEIN inviscid afterbody code. Instructions for the use of the modified CM3DT code with the QUICK and STEIN codes are included.		

TABLE OF CONTENTS

		<u>Page</u>
SECTION 1	INTRODUCTION	2
SECTION 2	IMPLEMENTATION OF QUICK GEOMETRY PACKAGE INTO CM3DT FLOW FIELD CODE	4
SECTION 3	COUPLING OF CM3DT AND STEIN FLOW FIELD CODES	13
SECTION 4	USER'S GUIDE TO THE MODIFIED CM3DT CODE	19
SECTION 5	REFERENCES	24

Accession For	
NTIS GRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A	

DTIC
ELECTE
DEC 28 1981
S D

SECTION 1

INTRODUCTION

This report details the coupling of the CM3DT inviscid nosetip flow field code to the STEIN inviscid afterbody flow field code. The CM3DT code, described in References 1 and 2, is a time-dependent code, in which the steady-state solution for supersonic/hypersonic flow over a nosetip is obtained as the asymptotic limit of the unsteady flow problem. The STEIN code, described in Reference 3, is a forward marching solution of the steady supersonic inviscid flow equations, and requires the specification of an initial flow field data plane, which must be obtained from a nosetip flow field code.

The STEIN code was specifically developed to treat complex geometries, such as the Space Shuttle Orbiter, and includes the ability to rigorously treat embedded shocks that occur in the flow field surrounding such configurations (e.g., wing shocks). To compute these complex configurations, STEIN uses a sequence of conformal transformations to produce a body-fitted computational coordinate system.

Geometries in the STEIN code are defined using the QUICK geometry system (Reference 4), which allows the definition of complex geometries (such as the Shuttle Orbiter) through specification of body cross-sections and meridional profiles.

The goal of this effort is to couple the CM3DT nosetip code to the STEIN afterbody code. This coupling involves relating the CM3DT and STEIN coordinate systems and developing an interpolation procedure for defining the initial data required for the STEIN code from CM3DT solutions. In addition, to ensure compatibility between CM3DT and STEIN, the QUICK geometry system has been implemented into CM3DT, allowing a single definition of a vehicle geometry to be used in both the nosetip and afterbody flow field codes.

The specific goal of coupling the CM3DT and STEIN codes was to obtain inviscid calculations on the Shuttle Orbiter at higher angles of attack than had been previously possible. Incorporation of the QUICK geometry package in CM3DT simplifies definition of the Shuttle Orbiter nosetip geometry, using existing descriptions of the Orbiter geometry in the QUICK format.

Section 2 of this report describes the implementation of the QUICK geometry system into the CM3DT code and details the relationship between the respective coordinate systems. The generation of initial data for the STEIN code is described in Section 3. A brief guide to the use of the QUICK/CM3DT/STEIN system of codes is provided in Section 4.

SECTION 2

IMPLEMENTATION OF QUICK GEOMETRY PACKAGE INTO CM3DT FLOW FIELD CODE

The QUICK geometry code was developed at Grumman Aerospace Corporation for NASA to provide a means of defining complex vehicle geometries in a relatively simple manner. This code was structured to allow its incorporation into flow field codes without modification. Details on the geometry models used in QUICK and instructions for its use may be found in References 4 and 5. (Codes to simplify the required inputs to QUICK are described in References 6 and 7).

The QUICK geometry system assumes a pitch plane of geometric symmetry; i.e., in the QUICK Cartesian coordinate system shown in Figure 2.1, the $x_Q - z_Q$ plane is a plane of symmetry. The geometric inputs to the QUICK code, which will not be discussed in this report, are defined in the (x_Q, y_Q, z_Q) coordinate system.

The output from the QUICK code used for geometric definitions in flow field codes is defined in a cylindrical coordinate system. Since QUICK does not permit the body radius in this cylindrical system to be multi-valued, provision has been made to allow for a "moving axis", which serves as the center of the (r, θ) polar frame within each cross-section $x_Q =$ constant. The moving axis is constrained to lie in the $x_Q - z_Q$ plane, and is defined by the curve $z_Q = d(x_Q)$, $y_Q = 0$. Figure 2.1 illustrates the resulting (r, θ, x_Q) coordinate system, which is related to the (x_Q, y_Q, z_Q) Cartesian system through

$$r = \sqrt{y_Q^2 + (z_Q - d)^2} \quad (2.1)$$

$$\theta = \tan^{-1} \frac{z_Q - d}{y_Q} \quad (2.2)$$

With the plane of symmetry assumption in QUICK, the polar angle θ is constrained to the range $-\pi/2 \leq \theta \leq \pi/2$.

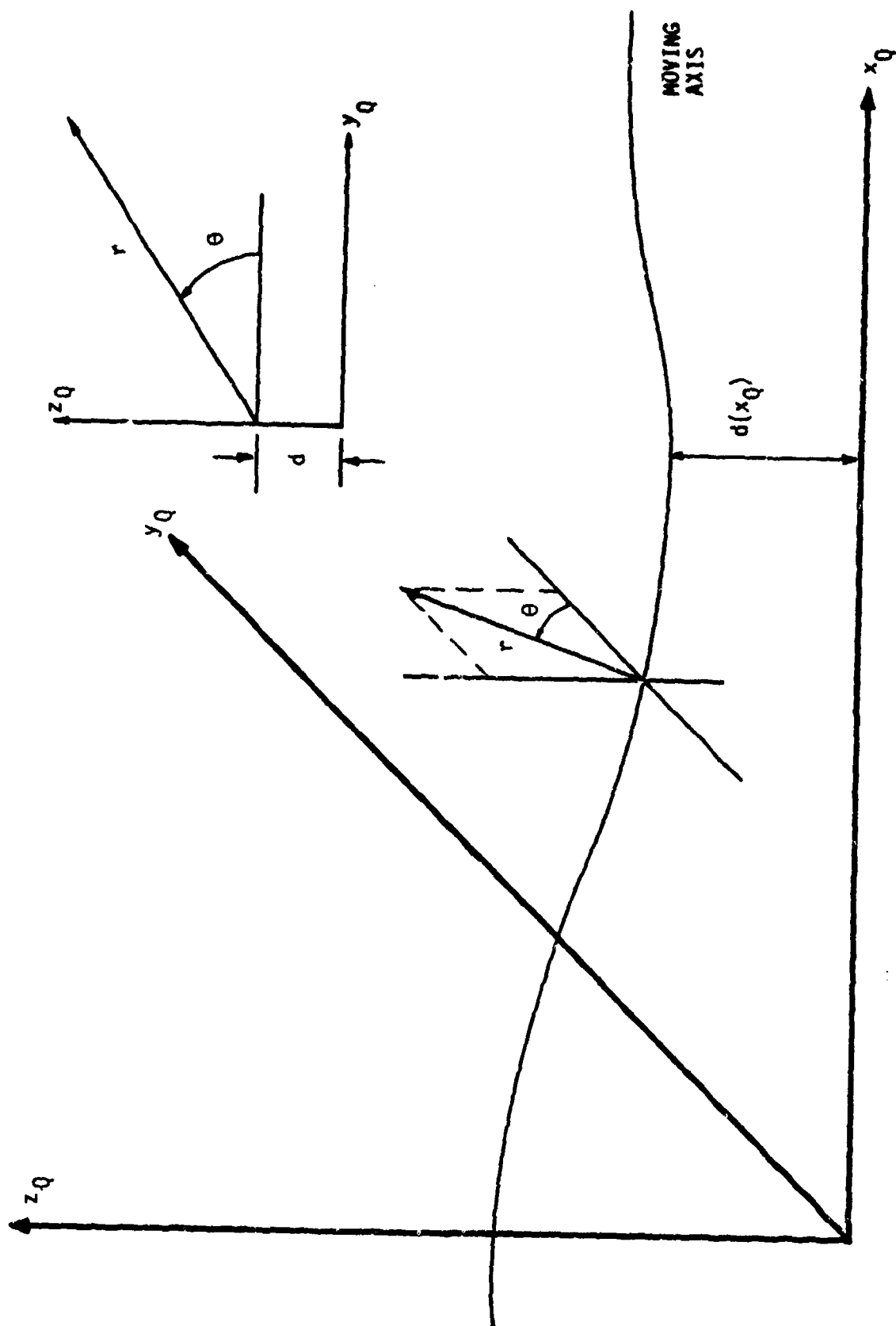


FIGURE 2.1. QUICK COORDINATE SYSTEMS

In the CM3DT nosetip flow field code the body geometry is defined in a cylindrical coordinate system (x, y, ϕ) , which is related to a corresponding Cartesian system (x_c, y_c, z_c) through

$$x_c = x \quad (2.3)$$

$$y_c = y \cos \phi \quad (2.4)$$

$$z_c = y \sin \phi \quad (2.5)$$

as shown in Figure 2.2; the polar angle ϕ is constrained to the range $0 \leq \phi \leq 2\pi$.

The QUICK and CM3DT coordinate systems are related by the specification of the parameters \hat{x}_{b0} and \hat{x}_0 , which are input to the CM3DT code as XBQ and XHQ, respectively (see Section 4). \hat{x}_{b0} represents the x_Q value of the most forward nosetip geometry point, and \hat{x}_0 is a second value of x_Q selected by the user of the code to define the nosetip computational axis.

The CM3DT computational axis is defined as the straight line that passes through the points $x_Q = \hat{x}_{b0}$, $y_Q = 0$, $z_Q = d(\hat{x}_{b0}) = d_1$ and $x_Q = \hat{x}_0$, $y_Q = 0$, $z_Q = d(\hat{x}_0) = d_2$ in the QUICK Cartesian coordinate system. This CM3DT axis lies entirely within the $x_Q - z_Q$ plane and is oriented at an angle δ_1 relative to the x_Q axis, where

$$\delta_1 = \tan^{-1} \frac{d_1 - d_2}{\hat{x}_0 - \hat{x}_{b0}} \quad (2.6)$$

as shown in Figure 2.3.

This angle δ_1 is similar in definition to the angle δ_1 (DEL1) used in the original formulation of CM3DT, as described in Reference 2. In the original CM3DT, the orientation of the nosetip axis to the afterbody axis is defined by the angles δ_1 , δ_2 , and δ_A , which are inputs to the code, where δ_1 and δ_2 define the pitch and yaw orientations of the nosetip axis relative to a bent afterbody axis, and δ_A is the bend angle of the afterbody axis. When using QUICK with CM3DT, due to the plane of symmetry assumption and moving axis assumptions of QUICK, δ_2 and δ_A must be zero (set internally by CM3DT), and δ_1 is computed automatically from Equation (2.6).

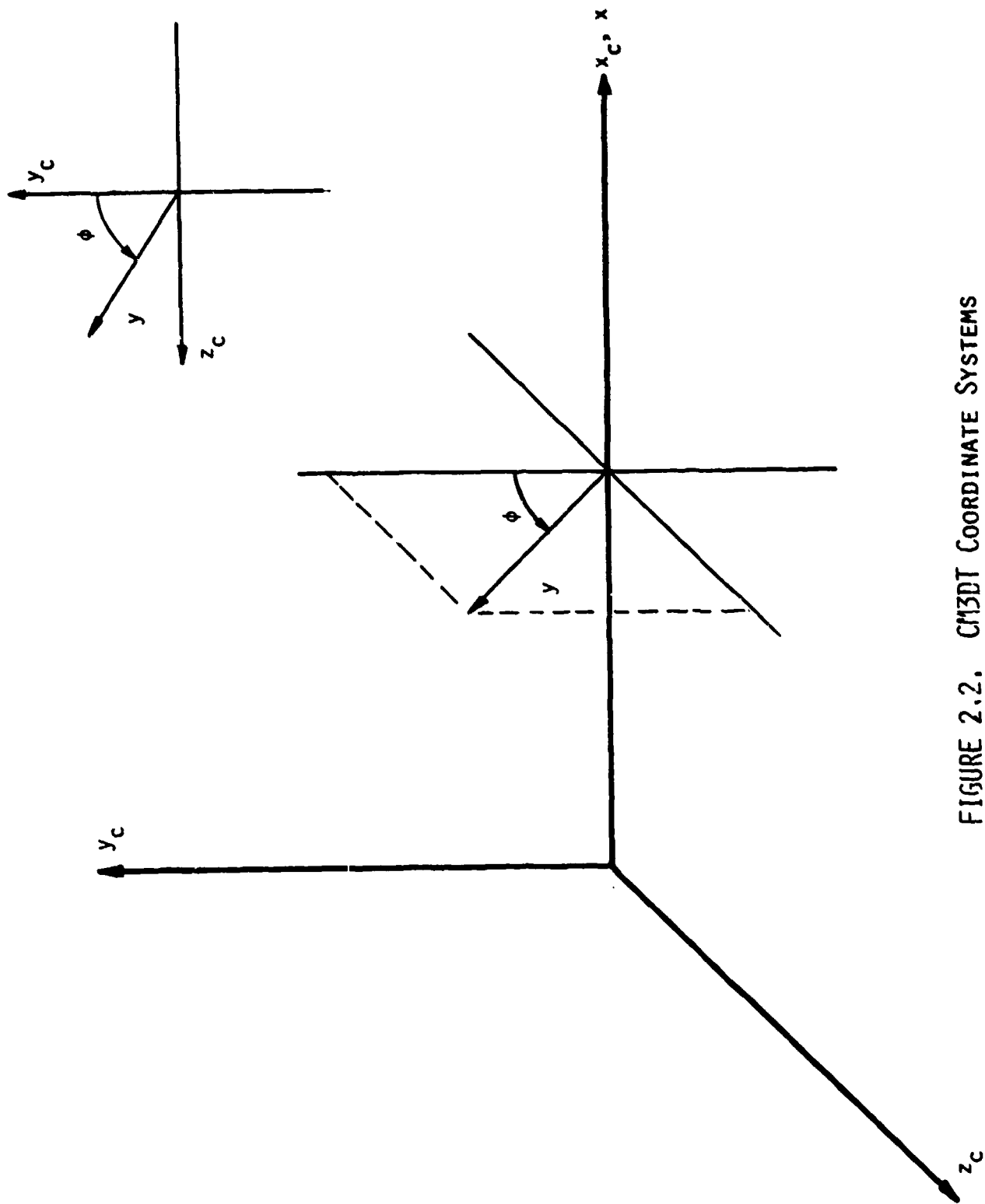


FIGURE 2.2. C13DT COORDINATE SYSTEMS

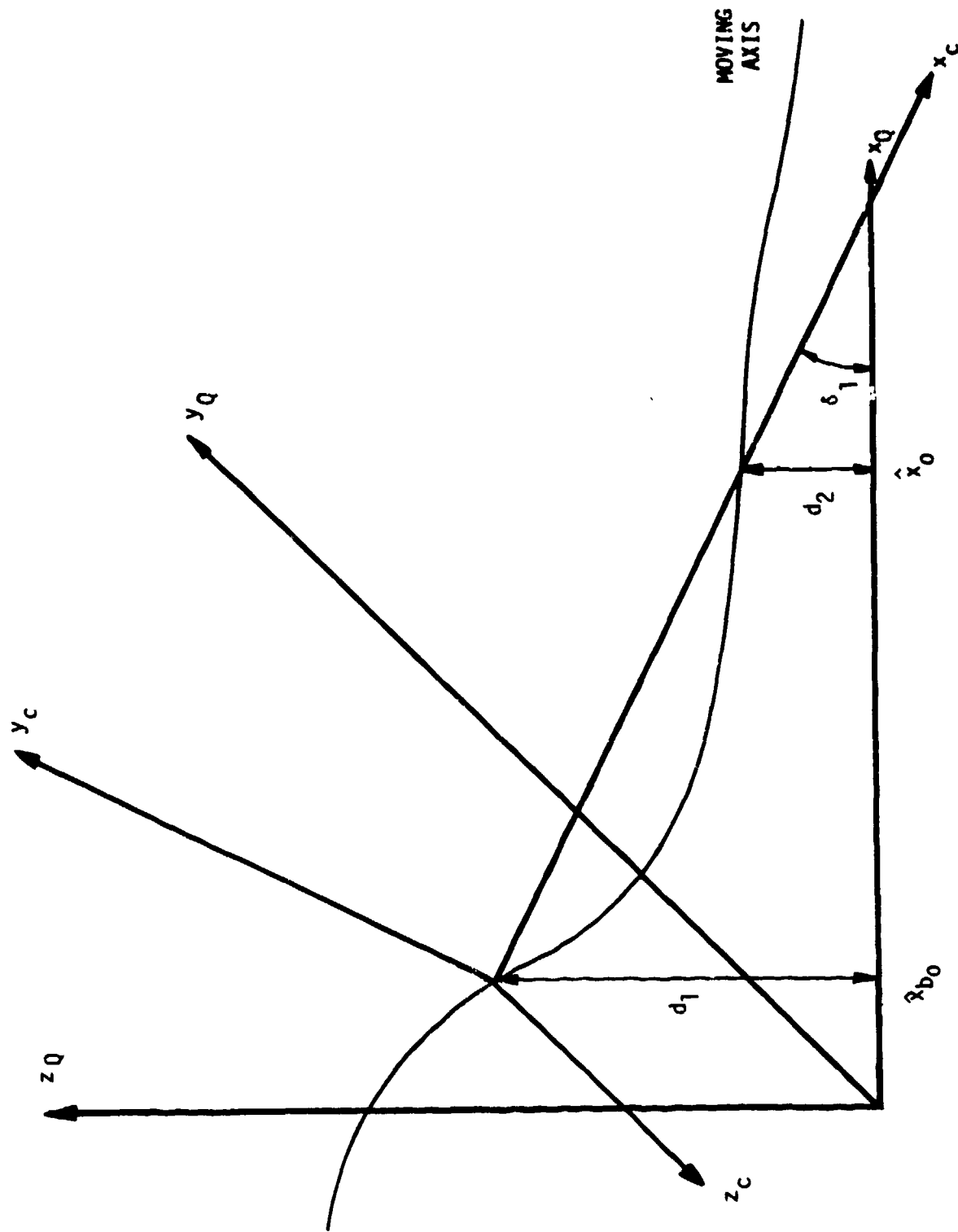


FIGURE 2.3. RELATIONSHIP BETWEEN QIICK AND CM3DT
COORDINATE SYSTEMS

In using CM3DT with the QUICK geometry definition, the angle of attack (α) and sideslip angle (β) are defined in the input relative to the x_Q axis. With $\delta_1 \neq 0$ and $\delta_2 = \delta_A = 0$, the pitch and yaw angles relative to the nosetip x (denoted by α_N, β_N) become

$$\beta_N = \beta \quad (2.7)$$

$$\alpha_N = \tan^{-1} \left[\frac{(\sin \delta_1 \cos \alpha + \cos \delta_1 \sin \alpha)}{(\cos \delta_1 \cos \alpha - \sin \delta_1 \sin \alpha)} \right] \quad (2.8)$$

(Although both the QUICK and STEIN codes assume a pitch plane of geometric symmetry and $\beta = 0^\circ$, the version of CM3DT modified to use the QUICK geometry system requires only the assumption of geometric symmetry. This new version of CM3DT retains the ability to treat non-zero sideslip. However, when using CM3DT to generate initial data for the STEIN code, geometric symmetry about the pitch plane and $\beta = 0^\circ$ must be assumed.)

Choosing $x_C = 0, y_C = 0, z_C = 0$ in the nosetip coordinates at the point corresponding to $x_Q = x_{b_0}, y_Q = 0, z_Q = d_1$ results in the following relationships between the QUICK and CM3DT coordinate systems:

$$x_C = (x_Q - x_{b_0}) \cos \delta_1 - (z_Q - d_1) \sin \delta_1 \quad (2.9)$$

$$y_C = (x_Q - x_{b_0}) \sin \delta_1 + (z_Q - d_1) \cos \delta_1 \quad (2.10)$$

$$z_C = -y_Q \quad (2.11)$$

$$x_Q = x_{b_0} + x_C \cos \delta_1 + y_C \sin \delta_1 \quad (2.12)$$

$$y_Q = -z_C \quad (2.13)$$

$$z_Q = d_1 - x_C \sin \delta_1 + y_C \cos \delta_1 \quad (2.14)$$

In the CM3DT code it is necessary to have the body geometry defined in the form $y = y_b(x, \phi)$. To develop this relationship for a geometry defined in the QUICK system an iteration is required, as outlined below.

Assuming that values of x and d are specified, an initial guess is made for y , and the corresponding values of (x_c, y_c, z_c) are computed using Equations (2.3) - (2.5). Values for (x_Q, y_Q, z_Q) are then determined from Equations (2.12) - (2.14). The corresponding values of r and θ are in turn determined from Equations (2.1) - (2.2).

It is important to note that CM3DT and QUICK use opposite half-spaces in treating problems with a pitch plane of symmetry. Thus, for values of ϕ in the range $0 \leq \phi \leq \pi$ the values of ϕ computed as outlined above will fall outside of the admissible range of θ , $-\pi/2 \leq \theta \leq \pi/2$. Since QUICK assumes a pitch plane of symmetry, however, the angle θ^* can be defined such that $r(x_Q, \theta) = r(x_Q, \theta^*)$, where $-\pi/2 \leq \theta^* \leq \pi/2$. As can be seen in Figure 2.4, θ^* may be defined as

$$\theta^* = \tan^{-1} \frac{z_Q - d}{-y_Q} \quad (2.15)$$

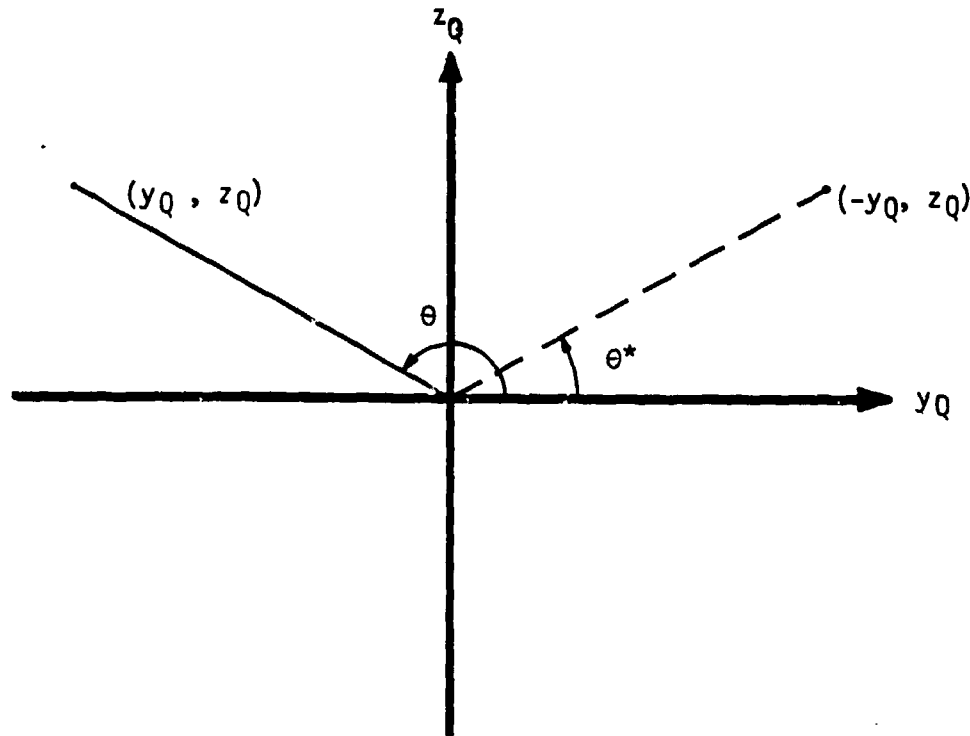


FIGURE 2.4. DEFINITION OF θ^*

Once Θ^* has been determined, the actual body radius is found from the QUICK geometry routines as $r = b(x_Q, \Theta^*)$.

This value of b is compared to the value of r computed from the originally assumed value of y ; if b and r are equal, the iteration is stopped. If b and r differ, another guess is made for y , and the iterative process is continued.

As described in Reference 1, the CM3DT code makes use of a transformed computational coordinate system that is fitted to the nosetip geometry. An iterative process is used in CM3DT to determine the image of the body surface, based on a definition of the body geometry of the form $y = y_b(x, \phi)$. Thus, when using the QUICK geometry option in CM3DT, a double iteration is required to relate the body surface in QUICK coordinates to the (x, y, ϕ) cylindrical system and then to the transformed computational coordinate system. Although this double iteration is not strictly required when using the QUICK geometry package in CM3DT, its use allows the retention of the other geometric definition options available in CM3DT, which are described in Reference 2.

In the definition of the body geometry in CM3DT, it is also necessary to define the body slopes $\partial y_b / \partial x$ and $\partial y_b / \partial \phi$. These values can be determined in terms of the slopes $\partial b / \partial x_Q$ and $\partial b / \partial \Theta$, which are provided from the QUICK geometry routines. By relating the expressions for the outward body normal in both the CM3DT and QUICK coordinate systems, the desired body slopes are determined to be

$$\frac{\partial y_b}{\partial x} = \frac{\sin \delta_1 N_3 - \cos \delta_1 N_1}{D} \quad (2.16)$$

$$\frac{\partial y_b}{\partial \phi} = \frac{y_b}{D} [\sin \delta_1 \sin \phi N_1 + \cos \phi N_2 + \cos \delta_1 \sin \phi N_3] \quad (2.17)$$

where

$$D = \sin \delta_1 \cos \phi N_1 - \sin \phi N_2 + \cos \delta_1 \cos \phi N_3 \quad (2.18)$$

$$N_1 = -\frac{\partial b}{\partial x_Q} - d_{x_Q} \left(\sin \theta - \frac{\cos \theta}{r_b} \frac{\partial b}{\partial \theta} \right) \quad (2.19)$$

$$N_2 = \cos \theta + \frac{\sin \theta}{r_b} \frac{\partial b}{\partial \theta} \quad (2.20)$$

$$N_3 = \sin \theta - \frac{\cos \theta}{r_b} \frac{\partial b}{\partial \theta} \quad (2.21)$$

Note also that for $0 \leq \phi \leq \pi$,

$$\frac{\partial b}{\partial \theta} (x_Q, \theta) = -\frac{\partial b}{\partial \theta} (x_Q, \theta^*) \quad (2.22)$$

SECTION 3

COUPLING OF CM3DT AND STEIN FLOW FIELD CODES

The STEIN afterbody code, described in References 3 and 5, solves the steady inviscid flow equations using a forward-marching (in space) explicit finite difference procedure. For this approach to be applicable, the velocity component in the marching direction must be supersonic at all points in the shock layer. In addition, this forward-marching procedure requires the specification of an initial data surface which defines the complete flow field at a given station. This section describes the procedure used to generate initial data surfaces for the STEIN afterbody code from CM3DT nosetip flow field solutions.

The STEIN code is formulated in a generalized coordinate system which is fitted to body cross-sections through the use of conformal transformations. These conformal transformations are applied in the STEIN code for axial stations ($z = \text{constant}$) downstream of a user-specified point, $z = ZMAP2$; no conformal transformations are used for stations upstream of another user-specified point, $z = ZMAP1$. For $ZMAP1 < z < ZMAP2$, the conformal transformations are introduced gradually to provide a smooth transition to the complete mappings. When the conformal transformations are not applied (i.e., $z < ZMAP1$) a polar (r, θ) mesh is used within each cross-section, with mesh points equally spaced in θ and equally spaced in r between the body and shock surfaces.*

For simplicity, it is assumed in this coupling effort that the initial data plane to be generated for the STEIN code will be at a station where the conformal mapping procedure is not used, i.e., at $z \leq ZMAP1$. Thus, the initial data to be generated from the CM3DT solutions is required to be in a polar coordinate system within the specified starting plane.

* The axial coordinate z in the STEIN coordinate system is equivalent to x_Q in the QUICK coordinate system.

Inputs required to the routine in which the initial data surface is generated are ZSTART, NC1, and MC1, where ZSTART is the initial value of z for the STEIN calculation, NC1 is the number of points in the radial direction and MC1 is the number of points in the circumferential direction. (These parameters have the same definition in this application as in their use as input parameters to the STEIN code.) With these parameters, the STEIN mesh points are located in polar coordinates at $z = ZSTART$ as

$$\theta_m = -\pi/2 + (m-1)/(MC1-1) \pi; \quad (3.1)$$

$$m = 1, 2, \dots, MC1$$

$$r_{n,m} = b(z, \theta_m) + (n-1)/(NC1-1) [c(z, \theta_m) - b(z, \theta_m)]$$

$$n = 1, 2, \dots, NC1 \quad (3.2)$$

where $r = b(z, \theta)$ represents the body surface and $r = c(z, \theta)$ represents the bow shock surface.

The first step in the generation of the initial data is to determine the location and slopes of the body points in the initial data plane from the QUICK geometry routine. Next, it is necessary to locate the bow shock points $r = c(z, \theta_m)$; since the bow shock location is known in CM3DT coordinates as $y = y_s(x, \phi)$, an iterative interpolation procedure is required. The relationships between the STEIN (QUICK) and CM3DT coordinate systems used in this procedure are detailed in Section 2.

Once the bow shock point $r = c(z, \theta_m)$ has been located in CM3DT coordinates, the bow shock slopes $\partial y_s / \partial x$ and $\partial y_s / \partial \phi$ may be readily determined through interpolation. These shock slopes may be expressed in the STEIN coordinate system as $\partial c / \partial z$ and $\partial c / \partial \theta$, which can be computed from

$$\partial c / \partial z = -N_2/N_1 - d_z (\sin \theta - \frac{\cos \theta}{c} \partial c / \partial \theta) \quad (3.3)$$

$$\partial c / \partial \theta = -c N_3/N_1 \quad (3.4)$$

where

$$N_1 = -\cos \theta \sin \phi + \cos \theta \cos \phi y_{s\phi} / y_s +$$

$$\sin \theta \sin \delta_1 y_{sx} + \sin \theta \cos \delta_1 (\cos \phi +$$

$$\sin \phi y_{s\phi} / y_s) \quad (3.5)$$

$$N_2 = -y_{sx} \cos \delta_1 + \sin \delta_1 (\cos \phi + \sin \phi y_{s\phi}/y_s) \quad (3.6)$$

$$N_3 = \sin \theta \sin \phi - \sin \theta \cos \phi y_{s\phi}/y_s + \cos \theta \sin \delta_1 y_{sx} + \cos \theta \cos \delta_1 (\cos \phi + \sin \phi y_{s\phi}/y_s) \quad (3.7)$$

In using the above formulae, care must be taken to ensure that the correct values of ϕ and $\partial y_s / \partial \phi$ are used. For a given point (r, θ, z) , where $-\pi/2 \leq \theta \leq \pi/2$, the corresponding point in the (x, y, ϕ) CM3DT coordinates will lie in the range $\pi \leq \phi \leq 2\pi$. The interpolation process is carried out in the CM3DT system using the circumferential angle ϕ^* , where, with a pitch plane of symmetry,

$$\phi^* = 2\pi - \phi \quad (3.8)$$

so that $0 \leq \phi^* \leq \pi$. From the symmetry conditions,

$$y_s(x, \phi) = y_s(x, \phi^*) \quad (3.9)$$

$$y_{sx}(x, \phi) = y_{sx}(x, \phi^*) \quad (3.10)$$

$$y_{s\phi}(x, \phi) = -y_{s\phi}(x, \phi^*) \quad (3.11)$$

Once the body and bow shock points have been located in the STEIN initial data plane, the location of all STEIN mesh points in this plane can be easily determined from Equations (3.1) and (3.2). Knowing (r, θ, z) in the STEIN coordinate system, the corresponding (x, y, ϕ) in CM3DT coordinates is easily determined using the transformations presented in Section 2. With the corresponding (x, y, ϕ) known for a given mesh point in the initial data plane, the dependent variables of the CM3DT flow field solution at that point are readily determined by interpolation.

As described in Reference 1, the CM3DT flow field variables are P, u, v, w , and s/R , where $P = \log p$ and u, v, w are the velocity components in the (ξ, η, θ) transformed space. Prior to interpolating for the required flow field data, the CM3DT velocity components are transformed to the (x, y, ϕ) velocity components, written as U, V, W , respectively, as

$$U = u\tilde{C} - v\tilde{S} \quad (3.12)$$

$$V = u\tilde{S} + v\tilde{C} \quad (3.13)$$

$$W = w \quad (3.14)$$

where $\tilde{C} + i\tilde{S} = e^{-i\omega}$, as defined in Reference 1.

It must again be noted that the interpolation is carried out in terms of $\phi^* = 2\pi - \phi$, where $0 \leq \phi^* \leq \pi$. The symmetry conditions applied to the CM3DT flow variables are

$$P(x, y, \phi) = P(x, y, \phi^*) \quad (3.15)$$

$$s/R(x, y, \phi) = s/R(x, y, \phi^*) \quad (3.16)$$

$$U(x, y, \phi) = U(x, y, \phi^*) \quad (3.17)$$

$$V(x, y, \phi) = V(x, y, \phi^*) \quad (3.18)$$

$$W(x, y, \phi) = -W(x, y, \phi^*) \quad (3.19)$$

In STEIN the dependent thermodynamic variables used in the calculation are defined as

$$P = \log(\bar{p}/\bar{p}_\infty) \quad (3.20)$$

$$s = (\bar{s} - \bar{s}_\infty)/C_{v\infty} \quad (3.21)$$

where $(\bar{\quad})$ denotes a dimensional quantity. The STEIN velocity components are defined as u_s , v_s , and w_s , which correspond to the Cartesian directions y_Q , z_Q , x_Q (in QUICK coordinates), respectively. The dimensional velocity components are defined from

$$\bar{u}_s = -V \sin\phi - W \cos\phi \quad (3.22)$$

$$\bar{v}_s = -U \sin\delta_1 + V \cos\delta_1 \cos\phi - W \cos\delta_1 \sin\phi \quad (3.23)$$

$$\bar{w}_s = U \cos\delta_1 + V \sin\delta_1 \cos\phi - W \sin\delta_1 \sin\phi \quad (3.24)$$

and the non-dimensional values are determined from

$$u_s, v_s, w_s = \bar{u}_s, \bar{v}_s, \bar{w}_s / \sqrt{\bar{p}_\infty / \bar{\rho}_\infty} \quad (3.25)$$

In determining the starting line data the quantities P , s , u_s , and v_s are determined by the interpolation procedure. The remaining velocity component, w_s , is determined from the requirement of constant total enthalpy in a steady inviscid flow, from

$$w_s = [2 (H_0 - h) - (u_s^2 + v_s^2)]^{1/2} \quad (3.26)$$

where H_0 is the total enthalpy and the static enthalpy is obtained in the form $h = h(p, s)$.

After determining the required initial data surface for the STEIN code from the CM3DT solution, it is necessary to evaluate the force and moment integrals on the nosetip, and relate these to the STEIN coordinate system if the subsequent STEIN calculation is to include force and moment computations. The integrations are carried out in the CM3DT coordinate system, and it is thus necessary to define the downstream limits of integration of the form $x = x_E(\phi)$, which is determined by transforming the body points in the STEIN initial plane to (x, y, ϕ) coordinates and interpolating to find the values x_E in the ϕ planes used in the CM3DT calculation.

With the assumption of a pitch plane of symmetry only two forces are present, the axial and normal forces. These forces may be evaluated as (assuming zero base pressure)

$$F_{AN} = 2 \int_0^\pi \int_{x_{B0}}^{x_E(\phi)} p y_b y_{bx} dx d\phi \quad (3.27)$$

$$F_{NN} = -2 \int_0^\pi \int_{x_{B0}}^{x_E(\phi)} p y_b (\cos\phi + \sin\phi / y_b y_{b\phi}) dx d\phi \quad (3.28)$$

The pitching moment (which is the only non-zero moment with a pitch plane of symmetry) is referenced to a point (x_{c1}, y_{c1}, z_{c1}) in the CM3DT Cartesian coordinate system. The point (x_{c1}, y_{c1}, z_{c1}) is determined from the transformation from QUICK coordinates of the moment reference point (x_{Q1}, y_{Q1}, z_{Q1}) , which are defined in the STEIN code through the inputs $VMO(3) = x_{Q1}$, $VMO(1) = y_{Q1}$, and $VMO(2) = z_{Q1}$. In STEIN it is assumed that $VMO(1) = y_{Q1} = 0$; thus it follows that $z_{c1} = 0$. The resulting expression for nosetip pitching moment is

$$\begin{aligned}
M = 2 \int_0^\pi \int_{x_{B0}}^{x_E(\phi)} p y_b [x (\cos\phi + \sin\phi/y_b y_{b\phi}) \\
+ y_b y_{bx} \cos\phi] dx d\phi \\
+ x_{c1} F_N - y_{c1} F_A
\end{aligned} \tag{3.29}$$

Finally, the axial and normal forces in CM3DT coordinates can be related to the STEIN coordinate system through

$$F_A = \cos\delta_1 F_{AN} + \sin\delta_1 F_{NN} \tag{3.30}$$

$$F_N = -\sin\delta_1 F_{AN} + \cos\delta_1 F_{NN} \tag{3.31}$$

In addition to the nosetip force and moment integrals, the initial data for STEIN also includes the nosetip surface area. This quantity is determined from evaluating the integral

$$A = 2 \int_0^\pi \int_{x_{B0}}^{x_E(\phi)} y_b \sqrt{1 + y_{bx}^2 + y_{b\phi}^2/y_b^2} dx d\phi \tag{3.32}$$

The initial data generated for the STEIN code from a CM3DT solution is written on a binary file in a format compatible with the existing starting procedure in the STEIN code. The processes required to start a STEIN calculation using this procedure are described in the following section.

SECTION 4

USER'S GUIDE TO THE MODIFIED CM3DT CODE

The process of making a STEIN calculation with CM3DT-generated initial data requires three steps. First, the geometry of interest is defined using program QUICK, which produces an intermediate file or deck of geometry data. Second, the modified version of CM3DT (which includes the subset of QUICK routines known as SUB-QUICK) reads the intermediate geometry file, performs the nosetip calculation, and generates an output file of initial data for STEIN. Finally the STEIN program proceeds from the initial data plane generated by CM3DT. QUICK and STEIN are documented in References 4 and 5; this section describes modifications to CM3DT input and operation.

Load Sequence

CM3DT, when combined with SUB-QUICK, occupies 250000 octal words of memory on a CDC Cyber 176. This load sequence includes subroutine GEOM6 which generates geometry using the QUICK intermediate data file, but not subroutines GEOM3, GEOM4, GEOM5, or ACOEF, which treat other geometry options in CM3DT and are not used in this application. Also added to the load sequence are subroutines STSTEIN and CLCINT, which generate STEIN starting line data and perform a general purpose integration, respectively. In addition, the estimate of memory allocation presumes the loading of either subroutine PVE3DL or subroutine PVE3DNC but not both, as discussed in Reference 2. Thus, the list of subroutines to be compiled for execution of the modified CM3DT program is as follows:

CM3DT	SHOCK	GEOMIN	} SUB-QUICK
PVE3DL or PVE3DNC	STAGPT	CSGEOM	
HING3D	RGAS	CURVES	
GRID3D	CUFT1	BLMSET	
OUT3D	TBL1	CSMSET	
BFL3CM	IDEAL	BLGEOM	
MAP3D	RLERR	VDOTV	
GEOM6	TLU1	MDOTV	
STSTEIN	SHKTAB	THELIM	
CLCINT	FREE	CSMCOE	
	ATMP	CSMINT	
	CUFT2	CSCALC	
	ATERR	CSMFLT	
	LINB		
	TBL		
	AIR		

Modifications to CM3DT Input

Modifications to the CM3DT input consist of two types. Those changes which are necessary for the inclusion of the QUICK geometry capability are incorporated into namelist INPUT, while additional variables necessary for the generation of initial data for STEIN comprise a new namelist ST, which follows INPUT. Definitions of input variables which are new or have been altered are listed below:

Namelist \$INPUT

ALPHA	Angle of attack (degrees) relative to QUICK axis
BETA	Sideslip angle (degrees) relative to QUICK axis
IQUICK	≠ 0 when QUICK geometry used (default 0)
XBB(L)	x_Q values at $\phi = \text{PHIBD}(L)$ defining downstream boundary (NPHI values; PHIBD's generated automatically for $\text{NPHI} \leq 3$ or $\text{NPHI} = 4$ and $\text{ISA} = 2$)
XBO	x_Q value of most forward nosetip point
XHO	x_Q value used to define point on computational axis downstream of XBO

N.B.: When using CM3DT to generate initial data for STEIN, must have $\text{ISA} = 1$ (default) with $\text{BETA} = \text{DEL2} = \text{DELA} = 0.0$. DEL1 will be defined internally by CM3DT.

Namelist \$ST

ZSTART	Axial location (in QUICK coordinates) of initial data plane
MC1	Number of points to be generated in the circumferential direction
NC1	Number of points to be generated in the radial direction
IAERO	= 0 no aerodynamic coefficients to be computed in STEIN ≠ 0 generate initial force and moment values for STEIN
XQREF	Axial location of moment center in QUICK coordinates (equal to VMO(3) in STEIN input)
ZQREF	Vertical location of moment center in QUICK coordinates (equal to VMO(2) in STEIN input)
XQ1,D1XQ1	Axial and radial locations of the geometric stagnation point in QUICK coordinates. (These values need be input only for a restarted CM3DT solution, and can be obtained from the section of CM3DT output displaying QUICK geometry parameters.)

File Structure

In addition to the CM3DT solution file (TAPE21) two additional files must be declared local to the modified CM3DT program: the QUICK geometry data file (TAPE22) and the STEIN initial data file (TAPE23). The existence of the CM3DT solution file enables the generation of STEIN initial data without repeating the entire calculation. This is done by restarting the CM3DT solution and setting KSTART equal to KMAX. By this action, control is passed immediately to the initial data-generating subroutine STSTEIN. It should be noted that implementation of this procedure requires that the user include as input the variables XQ1 and D1XQ1, since these are not written on the solution file.

Sample Cases

Two sample cases are listed below. The first is a CM3DT calculation at Mach 24 and 20° angle of attack of the Shuttle Orbiter with generation of starting line data for STEIN at $z = 44.44$. The second case is similar to the first, except that the STEIN initial data is generated from an already completed CM3DT solution.

Sample Case 1

```
JOB,-----
ACCOUNT,-----
REQUEST,TAPE21,PF.
REQUEST,TAPE23,PF.
ATTACH,OLD1,CM3PL,ID=-----
UPDATE,P=OLD1.
FTN(I,B=CM3DT,L=0)
ATTACH,OLD2,QUICKPL,ID=-----
UPDATE,P=OLD2.
FTN(I,B=QUICK,L=0)
ATTACH,TAPE22,QUICKDATA,ID=-----
LDSET(PRESET=ZERO)
LOAD(CM3DT,QUICK)
EXECUTE.
EXIT,U.
CATALOG,TAPE21,CM3,ID=-----
CATALOG,TAPE23,CM3ST,ID=-----
7/8/9
*COMPILE CM3DT,PVE3DL,HING3D,GRID3D,MAP3D,GEOM6
*COMPILE BFL3CM,OUT3D,STSTEIN,CLOINT,STAGPT,SHOCK
*COMPILE RGAS,CUFT1,TBL1,IDEAL,RLERR,TLU1,SHKTAB
*COMPILE FREE,ATMP,CUFT2,ATERR,LINB,TBL
7/8/9
*COMPILE CURVES,GEOMIN,CSGGEOM,BLMSET,CSMSET,BLGEOM,VDOIV
*COMPILE MDOIV,THELIM,CSMCOE,CSMINT,CSCALC,CSMFLT
7/8/9
CM3DT(LAMBDA)          SHUTTLE W/QUICK GEOMETRY   MACH 24   ALPHA=20
$INPUT
  NMAX=6,MMAX=18,LMAX=9,
  KMAX=500,KOUT=500,KTAPE=250,
  AMINF=24.,ALPHA=20.,
  NPFI=2,XBB=60.,60.,XBO=0.,XHO=150.,
  RN=50.,JA=7,ILAM=1,IQUICK=1$
$ST
  ZSTART=44.44,MC1=31,NC1=15,
  IAERO=1,XOREF=840.7,ZOREF=375.$
6/7/8/9
```

Sample Case 2

```

JOB,-----
ACCOUNT,-----
ATTACH, TAPE29, CM3, ID=-----
COPY (TAPE29, TAPE21)
RETURN (TAPE29)
REWIND (TAPE21)
REQUEST, TAPE23, *PF.
ATTACH, OLD1, CM3PL, ID=-----
UPDATE, P=OLD1.
FTN (I, B=CM3DT, L=0)
ATTACH, OLD2, QUICKPL, ID=-----
UPDATE, P=OLD2.
FTN (I, B=QUICK, L=0)
ATTACH, TAPE22, QUICKDATA, ID=-----
LDSET (PRESET=ZERO)
LOAD (CM3DT, QUICK)
EXECUTE.
EXIT, U.
CATALOG, TAPE23, CM3ST, ID=-----
7/8/9
*COMPILE CM3DT, PVE3DL, HING3D, GRID3D, MAP3D, GEOM6
*COMPILE BFL3CM, OUT3D, STSTEIN, CLCINT, STAGPT, SHOCK
*COMPILE RGAS, CUFT1, TBL1, IDEAL, RLERR, TLU1, SHKTAB
*COMPILE FREE, ATMP, CUFT2, ATERR, LINB, TBL
7/8/9
*COMPILE CURVES, GEOMIN, CSGEOM, BLMSET, CSMSET, BLGEOM, VDOTV
*COMPILE MDOTV, THELIM, CSMCOE, CSMINT, CSCALC, CSMFLT
7/8/9
CM3DT (LAMBDA)          SHUTTLE W/QUICK GEOMETRY    MACH 24    ALPHA=20
$INPUT
  NMAX=6, MMAX=18, LMAX=9,
  KMAX=500, KSTART=500,
  AMINF=24., ALPHA=20.,
  NFHI=2, XBB=60., 60., XB0=0., XH0=150.,
  RN=50., JA=7, ILAM=1, IQUICK=1$
$ST
  ZSTART=44.44, MC1=31, NC1=15,
  XQ1=0., D1XQ1=335.,
  IAERO=1, XQREF=840.7, ZQREF=375.$
6/7/8/9

```

SECTION 5

REFERENCES

1. Hall, D. W., "Performance Technology Program (PTP-S II), Vol. III: Inviscid Aerodynamic Predictions for Ballistic Reentry Vehicles with Ablated Nosedtips," BMO TR-81-1, September 1979.
2. Hall, D. W. and Dougherty, C. M., "Performance Technology Program (PTP-SII), Vol. III: Inviscid Aerodynamic Predictions for Ballistic Reentry Vehicles with Ablated Nosedtips. Appendix: User's Manual," BMO TR -81-80, September 1979.
3. Marconi, F., Salas, M., and Yaeger, L., "Development of a Computer Code for Calculating the Steady Super/Hypersonic Inviscid Flow around Real Configurations, Vol. I, Computational Technique," NASA CR-2675, April 1976.
4. Vachris, A. and Yaeger, L., "QUICK Geometry - A Rapid Response Method for Mathematically Modeling Configuration Geometry," NASA SP-390.
5. Marconi, F. and Yaeger, L., "Development of a Computer Code for Calculating the Steady Super/Hypersonic Inviscid Flow around Real Configurations, Vol. II, Code Description," NASA CR-2676, May 1976.
6. Shope, F. L., "Simplified Input for Certain Aerodynamic Configurations to the Grumman QUICK-Geometry System (A PREKWIK User's Manual)," AEDC-TR-77-62, August 1977.
7. Shope, F. L., "Simplified Input for Certain Aerodynamic Nose Configurations to the Grumman QUICK-Geometry System (A KWIKNose User's Manual)," AEDC-TR-77-89, February 1978.

DISTRIBUTION LIST

Ballistic Missile Office
BMO/SYDT
Attn: Maj. K. Yelmgren (2)
Norton AFB, CA 92409

Defense Technical Information Center (2)
Cameron Station
Alexandria, VA 22314

Air University Library
Maxwell AFB, AL 36112

TRW DSSG
Attn: W. Grabowsky (2)
P. O. Box 1310
San Bernardino, CA 92402

TRW Systems Group (2)
Attn: J. Ohrenberger
M. Gyetvay
1 Space Park
Redondo Beach, CA 92078

Headquarters, Arnold Engineering
Development Center
Arnold Air Force Station
Attn: Library/Documents
Tullahoma, TN 37389

Armament Development and Test Center
Attn: Technical Library, DLOSL
Eglin AFB, FL 32542

Air Force Wright Aeronautical Laboratories (3)
Air Force Systems Command
Attn: M. Buck (AFWAL/FIM)
R. Neumann (AFWAL/FIMG)
V. Dahlem (AFWAL/FIMG)
Wright-Patterson AFB, OH 45433

U. S. Army Ballistic Missile
Defense Agency/ATC-M
Attn: J. Papadopoulos
P. O. Box 1500
Huntsville, AL 35807

Director, Defense Nuclear Agency
Attn: J. Somers (SPAS)
Washington, DC 20305

Naval Surface Weapons Center
Attn: Carson Lyons/K06
White Oak Laboratories
Silver Spring, MD 20910

Acurex Aerotherm
Aerospace Systems Division
Attn: C. Nardo
485 Clyde Avenue
Mountain View, CA 94042

Avco Systems Division
Attn: N. Thyson
201 Lowell Street
Wilmington, Mass 01887

General Electric Company
Attn: R. Neff
3198 Chestnut Street
Philadelphia, PA 19101

Lockheed Missiles and Space Co.
P. O. Box 504
Attn: G. T. Chrusciel
Sunnyvale, CA 94086

McDonnell Douglas Astronautics Co.
Attn: J. Copper
5301 Bolsa Avenue
Huntington Beach, CA 92647

PDA Engineering
Attn: M. Sherman
1560 Brookhollow Drive
Santa Ana, CA 92705

Sandia Laboratories
P. O. Box 5800
Attn: Library
Albuquerque, NM 87115

Science Applications, Inc.
Attn: A. Martellucci
994 Old Eagle School Road
Suite 1018
Wayne, PA 19087